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Casing Failure Characteristics, Prevention and Control Strategies for Mature Oilfields

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Abstract. As the oil and gas fields enjoy a longer and longer production life, casing damaged wells in oil and gas fields increase year by year in number. Assets are at expense, costs are increased, and production is threatened. In this paper, the status and mechanism of casing failures in China, USA and Russia are investigated; factors and prevention and intervention measures are analyzed; casing failure types, intervals, times and causing factors are studied; failure characteristics and causes types of mature oilfields are compared and evaluated; and for each different-factor that causes casing failure a corresponding prevention or intervention method is suggested. The studies on casing failure mechanism, detection technology and modeling by overseas countries are worth of reference, and correlative technologies are significant guidance for casing failure prevention and control in our mature oilfields.

1. Introduction

As oil and gas fields development continues, casing damaged wells increase in number year by year. Especially in mature oilfieds where the casing mechanism is complex and the problem of casing failure is extra severe, the production is adversely impacted. So the casing failure characteristcs and prevention and control measures of mature oilfields at home and abroad are investigated and correlated and compared, covering the worldwide oilfields casing failures and researches. For mature oilfields at home, research direction and prevention and control strategy are proposed.

2. Current state of research

From the literature at home and abroad over the years, it is learnt that the researches for casing failure in fields of all over the world is at peak. For oilfields in China, due to the various types of reservoir and long time production, the causing factors and mechanism for casing failure are diverse, so the controlling factor of casing failure needs to be further understood.

In 2015, CNPC's number shows an accumulative casing failure rate of 13.23%, 3 million tons of oil is taken short and about 1700 casing damaged wells call for workover every year (Liu, 2018).

Russion oil companies also have an increasing number of invalid wells year by year. The statistics show that the TNK-BP company takes up the biggest share of 26.9 %(2003 to 2011). In 2015, the accumulative casing failure rate for 8 Russian companies is 1.78%-4.13 %(Fig. 1) [1-2].

Davis et al. in 2014 investigated 380 000 oil and gas wells in Canada, Netherland, Norway offshore, British and USA, of which 7% have integrity issues of diffirent extent. Specific wellbore integrity issues vary depending upon the different types of conventional and unconventional reservoirs, vertical versus horizontal wells, onshore versus offshore and special types of well designes, purpose and

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operations. Well integrity issues are most commonly associated with the cement quanlity, casing corrosion, dynamic drilling and production pressures, and completion [3].

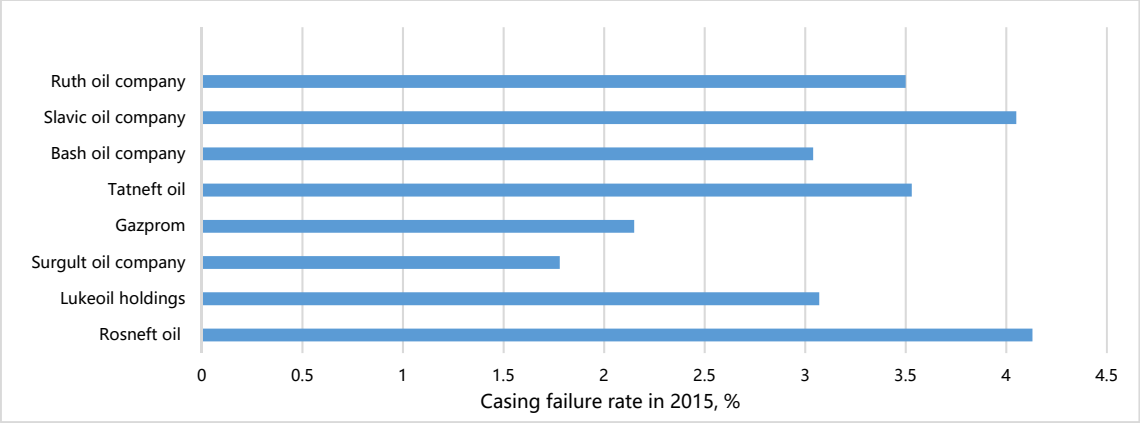


Figure 1. Casing failure rates of Russian oil companies.

3. Research progress of casing failure mechanism

The study for casing failure mechanism in china started in 1980s, but due to the complex influencing factors, no systematic research worlflow and method have been formed yet (Fig. 2); many Russian oilfields are located near to arctic circle, and the main reason for casing failure is the effect of rock formation melting around tundra and the deformation of producing casing due to heating. In oilfields in Europe and America, mechanism for casing failure covers chemical, mechanical and physical aspects. Chemical reactions are the most common aspect of all well integrity issues, and often lead to dissolution of cement and corrosion of casing. The basic compounds in cement consists of various oxides of calcium and silicon, whose reaction of CO_2 and H_2S deplet the calcium at the cement surface and reduce the cement mechanical strength. Acid water, high temperature and high pressure environments and critical CO_2 act as catalysts for the chemical reactions involved in steel casing corrosion. The redox reaction takes place at the surface of the casing, and the byproduct results in the formation of carbonate scales at the surface. Mechanical mechanism focuses on geomechanical stress. The changing stress regimes have been attributed to several parameters such as pressure differential created in the system during consistent production and injection, changes in temperature, impacts of tectonic activities, the eccentricity of the casing, existing fractures, leakage at casing shoes, and chameical alteration, which in turn lead to radial cracking, plastic deformation in cement, de-bonding between cement and casing or formation, and voids in the cement (Raj Kiran，2017). Physical factors are often related to methods of operational procedure and use of materials, such as drilling, cementing and completion. Hydrochloric acid and hydrofluoric acid are used in certain types of the reservoir to improve formation permeability, which is very destructive to cement. For example, a case study in Prudhoe Bay showed that 37% of primary cement job developed zonal-isolation problems and 73 of squeeze cement jobs broke down after HCl/HF treatment [4].

Table 1. Progress of research on casing failure mechanism in China.

1980s	1990s	Since 2000
Fesearches on high pressure water injection, unreasonable water flooding, mudstone creep, casing confining pressure and load on casing were carried out	“Mechanical system for complex formation” and finite element analysis on high pressure water injection were proposed for the first time in 1993; cement sheath thickness, casing wall thickness, effects on casing load distribution	Research on stress was strengthened, stress-pressure model established, casing failure mechanism in complex fault depression studied by elastoplastic fluid-solid coupling model; horizontal casing failure; clay layer fault depression

4. Casing failure characteristics

In the worldwide research, there are not any uniform types for casing failures yet. In this paper, taking all casing failure types of oilfields in China, Russia, Europe and America into consideration, casing failures are classified by mechanics, including necking, bending, breaking and leaking. Necking and bending can be called by a joint name of deforming. The responding mechanical characteristics are collapsing, axial buckling, shearing and corrosion (Fig. 2) (Liu, 2018).

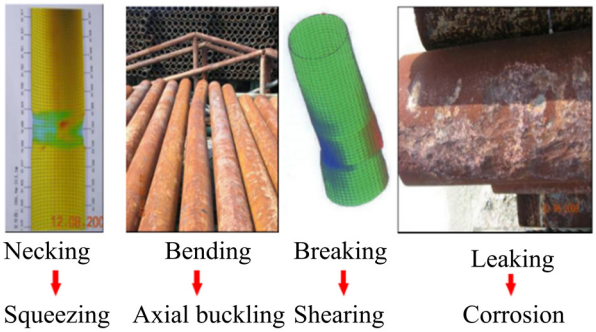


Figure 2. Mechanical categories of casing failures.

Through comparasion and analysis, it can be seen that casing failures of oilfields in different countries have different characteristics in casing failure types, intervals, times and influencing factors.

In terms of casing failure type, most casing failures in Daqing, Shengli and Jilin oilfields fall in the category of deforming [5]. Deforming and breaking take up 95% of casing failures in Daqing and Jilin oilfields. In Shengli oilfield, types of casing failure are vaious and evenly distributed [6] (Fig. 3).

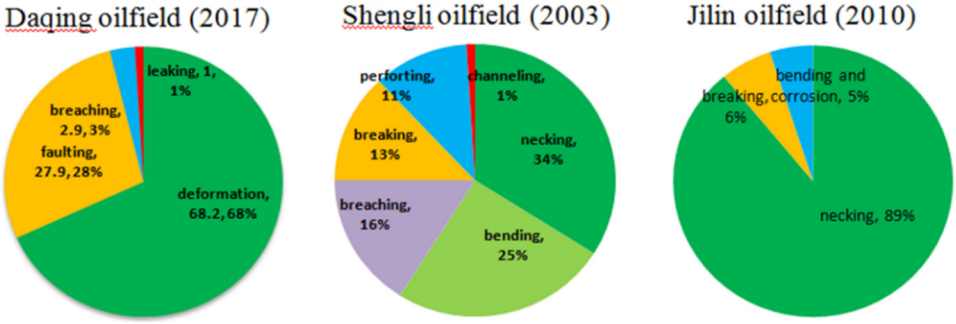


Figure 3. Casing failure types of Chinese oilfields.

In terms of casing failure intervals, Daqing oilfield could be divided into 4 sections horizontally: shallow section (9.10%), N 2 index bed (24.07%, with the key blocks deducted 18.1%), Sa 0-Sa II4 (37.14%), oil beds (29.69%). Shengli oilfield could also be divided into 4 sections horizontally: higher than top of cement (16%), between top of cement and top of oil formations (25%), from top to bottom of oil formaitons (55%) and lower than bottom of oil formations (4%) (Fig. 4) [6]. Casing failures in Jilin oilfield concentrate in the shale fracture zone between Fuyu formation and the seal Qinshankou formation, where the rate is 67.1% [5].

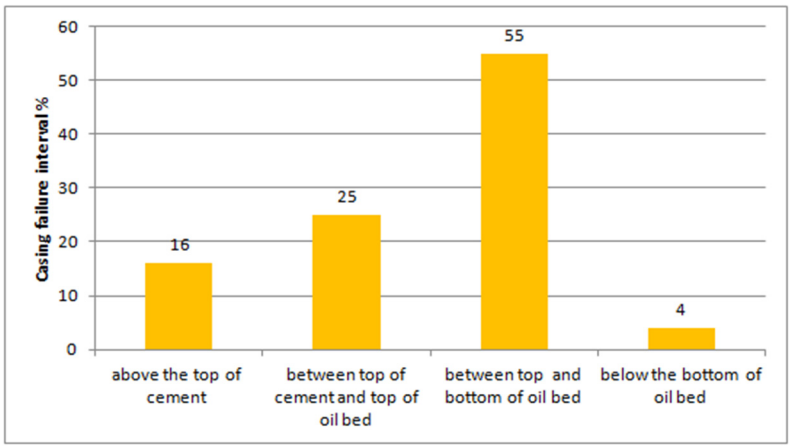


Figure 4. Casing failure intervals of Shengli oilfield.

In terms of casing failure times, it is observed that the number of casing failure wells is closly related to development stages of oilfield. There are 3 peaks of casing failure in Daqing oilfield history. The first peak happened in 1986 in the non-oil intervals of N 2 section, all the casing damaged wells were stressed in the same direction, and most of the failures are deforming; the second peak happened in 1996 and most failures are faulting; the third peak in 2011 took place mainly in N 2 bottom in various types, and the stress directions are different [7]. Shengli oilfield started water flooding between 1987 and 1988 and adjusted the injectors and producers in 1990 to 1993, where the number of casing damaged wells saw continuous increases, and the average normal production time was only 11 years. 23% of casing damaged wells has failures less than 23%, 41% between 6-10 years, 24% between 11-15 years and 12% over 15 years [8]. Fuyu oilfield of Jilin discovered no casing damaged wells during 1960-1972 the dissolved gas flooding and after 1973 the overall water injection the number of casing damaged wells started to increase year by year. The average time for casing to be damage was 10.21 years [5].

Casing failure is the result of many effects. The causing factors of casing failure include geological, casing, production, engineering and manmade factors. In China, surface and reservoir subsidence is not given enough attention. Casing failure caused by tundra is specific to Russia. In Europe, America and Russia, manmade factors in casing failure attract great attention (table 2).

Table 2. Causes of casing failure and prevention and control measures.

Casing failure causes		Prevention and control measures
Geological factors (internal cause)	Structural: faults, dips, fractures, texture, fracture zone	4 categories of conventional techniques: casing designe optimization, drilling engineering designe optimization, well deployment optimization and submersible electronic centrifugal pump
	lithology: shale, oil shale, sandstone	7 categories of conventional methods, including sand production prevention for oil beds, bilayer assembling casing, improving cementing quanlity, anti-swelling agent for water injector, improving steel grade, prolonged surface casing and casing reaming
	Corrosion: surface water, formation water,injected agent	12 categories of conventional techniques, including small casing repaire, cathode protection, expandable tube compensation, lateral drilling, chemical plugging, returning top of cement to well head, whole well thickening, improving steel grade at oil beds, salt and corrosion reagent injection, M1-X packer+ corrosion coated tube+preservative solution in casing space, installing polythene tail pipe to the receiving part of the pump; 1 feature technique: installing innovative casing packing pad to block the casing beds
	Stratum subsidence(ground stress)	1 feature technique studying the effect of stratum subsidence on caising failure, for instance, a Southern American foreland basin stress was studied by analyzing model, and the biggest horizontal subsidence distance was 2.4cm
	Tundra	-
Casing pipe factors (internal cause)	Structure designe, steel grade, drawback,intensity, screw thread	2 conventional measures, including upgrading steel to P110, thickening casing walls; 1 feature measure, to study casing failure by ground stress and designe casing at tubing section

Development factors (external cause)	Well pattern deployment: cutting well pattern, areal well pattern, well deployment method	2 conventional measures, line flooding and diamond shaped well pattern
	Abnormal high pressure	1 feature technique, workability operational limits table was established to study the relation between drawdown and depletion and safe zone for operation was recommanded
	Over pressure water injection; injection-production ratio imbalance	7 conventional measures, using reasonable water injection standard, injection pressure, unload rate, decompression and augemented injection, small casing, double packer and re-perforation;5 conventional measures: pressure limiting producing, water injector operation quanlity control, well washing, swelling prevention and plug removal
Engineering factors	Sand production, drilling dogleg	5 conventional techniques: packer out of casing at the top of oil formation, construction displacement control during fracturing, keeping away from faults and top and bottom
	Casing quanlity, well cementing and completion	
	Workover, perforation, fracuring	
Manmade factors (subjective cause)	Experience and level of the operating personnel	-

5. Casing failure prevention and controlling

In terms of casing failure prevention and controlling, prevention shall take precedence. Based on the 11 of 13 types of causes for casing failures (excluding Tundra and human causes) summarized in Table 1, and taking mature oilfields in and outside of China as examples, 54 conventional technologies are summed up, including casing design optimization, drilling design optimization, well placement alteration, submersible electronic centrifugal pumps and etc., as well as 4 special technologies, including MaxWell Expandable Liner System and etc., and 5 emerging technologies including visual logging technology.[5-20] The conventional technologies have been used in a variety of reservoirs in China and other countries, which have slowed down the increase of casing damage to a certain extent. Other technologies are seldom used or not used at all in Daqing Oilfield.

5.1 Special technologies for preventing and controlling casing failure

5.1.1 MaxWell expandable liner system for repairing casing failure. From December 2014 to March 2015, the MaxWell Expandable Liner System developed by Mohawk Energy was used by Lukoil PJSC in a field pilot conducted in Bofu oil and gas field to repair 3 casing damaged wells with casing leaks at the depth ranging from 1856m to 1915m. The casing leaks resulted in loss of 250m^3 injected water at the casing damaged section. After installing 59m plugging mat to seal the leaking section, losing of injected water from casing damaged section was stopped [21].

5.1.2 Well operability limit model. Ann Mag Field is located in South Texas and its formation material consists of a mixture of shale, shaly siltstone, calcareous shaly siltstone, and small amounts (<10 to 20%) of calcareous, shaly, very fine-grained sandstone. The sand formations are over pressured. From 1998 to 2011, casing damage was experienced in 11 out of the 18 wells that have been drilled in the area; i.e., nearly 61% of total wells were damaged during their production life. For the failure problems, 61% had casing collapse, 8% had casing parting, and 31% were fill/sand production problems. At the same time, most of the failure locations were in shale zones, which accounts for 62% of the failure. Only 38% failure occurred in the perforation zones. The factors affecting casing failure include: 1) the formation pressure dropped during waterflooding and the casing was subjected to additional axial pressure which caused the formation to slip. In the fault block and fracture formation (Shengli and Jilin Oilfields), as the dip angle becomes larger, the casing damage becomes more severe; 2) casing damage was caused by engineering factors such as perforating operations [22].

Several measures were taken to solve these problems, including:Use new cement generation, like “ELASTIC CEMENT”, to improve the quality of well cementing;Use swellable packer in the shale

zone section, and fracture jobs should be done as far from shale and fault to minimize the risk of slippage;Use high grade and thicker casing for the fault section to strengthen the well against collapse;Produce in commingled to maintain bottomhole pressure and reduce the pressure differentials between the bottomhole pressure and the formation pressure surrounding the casing. And this is better for formation stability; Establish a well operability limit (WOL) graph and design production strategy/methodology in the safe zone. If the operation has to be made in zone I, the operation should be as short as possible (Figure 5).

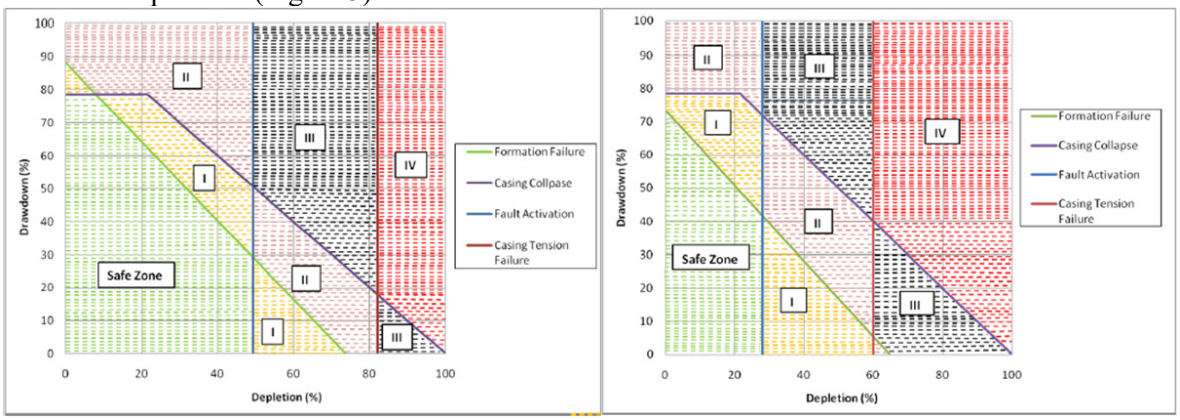


Figure 5. Workability operational limits for sandstone (right) and shale (left).

5.2 New casing damage detection technologies

With the development of artificial intelligence technologies, the focus of casing failure detection has shifted to real-time diagnosis and identification of leaking depth and radial location. At present, there are two representative technologies: visual logging technology and acoustic wave array technology.

*5.2.1 Visual logging technology.*Visual logging technology enables real-time well integrity diagnostics. It uses downhole cameras to conduct integrity diagnostics. It combines the digital imagery components with advanced image optimization algorithms. The latest technical improvments include: 10,000 psi of pressure rating, 5MPx digital imaging sensors, and 360° view coverage, 128 GB internal memory, and digital zoom, pan, and tilt during real-time (live) and offline inspection. Laboratory experiments and field tests have confirmed the effectiveness of this technology [23].

*5.2.2 Acoustic array technology.*Acoustic array technology can identify both the depth of casing leaks and radial location in the wellbore. It generates two-dimensional (2D) images of flow-generated noise, which can then be used to extract both leak-depth and radial location, and removes the high dependency on the frequency and magnitude to avoid the false echo of the leak location. With high accuracy, it makes operational planning more efficient and helps prevent nonproductive time [24].

5.3 Prediction modelling technologies for casing failure. The literature suggests that oilfields in countries other than China have put more efforts in preventing than in controlling casing failure, and models are built based on the comprehensive geological research to predict casing failure.

5.3.1 Analytical modelling. Geertsma first proposed an analytical model to predict the displacements above a reservoir based on poroelasticity (“Geertsma’s analytical method”) in 1973 and Geertsma’s analytical method has been continuously extended and improved over the years (See Table 3). The semi-analytical model based on viscoelasticity and three-dimensional (3D), nonlinear finite element method were used to build geologic model to predict stress changes in overburden and reservoir layer caused by well repair, production, corrosion, leaking, casing collapse and pressure depletion, and to predict the land subsidence and casing failure.

Table 3. Advancement of analytical models in the world.

Analytical prediction model	Type of reservoir/research subject	Representative literatures
Poroelasticity first proposed	Displacements above a disk-shaped reservoir	Geertsma,1973
Semi-analytical model based on viscoelasticity	Subsidence in a multilayered formation	Fokker, 2006
Extend geertsma's method	Displacement of brittle formations in tight reservoir	Tempone, 2010
Extend geertsma's method	Layered stratigraphy formations above the disk-shaped reservoir	Mehrabian, 2015
Extend geertsma's method	Real-time wellbore stability	Zhang Feifei, 2016
Calculation of overburden displacement and stress using pressure plot	Subsidence, shearing, casing damage	Peng Zhang, 2018
Relationships between land subsidence and casing shear failure		Bruno, 2001
Use a 3d nonlinear finite element method to simulate stress changes in overburden and reservoir intervals caused by reservoir depletion		Furui, 2012
Stress changes caused by repairing, prodcution decrease, corrosion, leakage, wellbore collapse		Schwall, 1994；Maurice, 2001；Furui, 2012

The analytical model was used to study the stress changes in a foreland basin located in South America. The analysis of strain and stress changes and casing load changes shows that the most obvious strain and stress changes occur in the zone the with the largest pressure drop in the reservoir; the maximum compressive stress is 20,620 psi if soil-casing interaction is considered, whereas the maximum compressive stress is 14,287 psi if no soil-casing interaction is considered. The results show that vertical displacements (subsidence) were 0.026 and 0.087 ft on the surface and at a depth of 10,165 ft, respectively. For grade N-80 steel casing, the safety factor decreases from 5.6 to 3.9[26].

5.3.2 Remaining useful life (RUL) prediction modelling. The Remaining Useful Life (RUL) Prediction Model proposed by Bibek Das et al. combines both statistical method and physics of failure approach. This model can make automatic diagnosis of upcoming production casing integrity problems by combining real time well condition data from simulations with drilling, completions and production data. The method can also help to extend the well life and optimize production plan. However, it should be noted that there are uncertainties in the prediction of stress that can influence the remaining useful life results [27-28].

RUL model was used to study a production casing sub-system: a P-110 grade casing with outer diameter of 5 inch and inner diameter of 4 inch. It is assumed that a horizontal well has a Kickoff Point (KOP) at about 12,000 ft. A 7″ production hole is drilled to through the build section. For sensitivity case the build rate angles chosen are 2°/100 ft. A soft-string model and a stiff-string model were used to estimate wear, the results show that 1) wear increases with increase in DLS thus causing higher reduction in casing strengths; 2) soft-string model yields a very conservative estimate while the stiff-string model gives a more realistic estimate.

*5.3.3 Data mining algorithms.*Noshi et al. from Texas A&M University first used data mining algorithms to conduct a predictive analytics of casing failure data. A predictive analytics software from SAS was used to analyze dataset of casing failure data from the Granite Wash play located in Texas and Oklahoma. 5 data mining methods were adopted, including 2 descriptive analytics method, namely PivotTables and ScatterPlots, and 3 Predictive analytics methods, namely Logistic Regression, Supervised Hierarchal Clustering, and Decision trees. A total of 26 different variables were analyzed, out of which 9 most important variables contributing to failure were determined by Logistic Regression, namely TVD, operator, frac start month, MD of most severe DL, heel TVD, hole size, BHT, total mass of proppant, cumulative DLS in lateral and build sections. The PivotTable showed that the rate of casing failure was highest during the winter season with five out of seven wells failing (71.4%), followed by the fall season with only two out of twelve wells failing (16.67%). The spring

season had seven out of twelve wells failing (58.33%), and finally, the summer season with six out of fourteen wells failed (42.86%). Other factors include: lack of cement, acid pumped, lateral section length, and DLS [29].

The casing failure warning software developed by Daqing Oilfield further extended the application of the big data mining technology. The software is based on an integrated sharing platform of data on casing damage investigation which can be used for data acquisition, processing and analyzing and consists of a display tool. It also integrated a casing damage index system, an early warning process and control measures, introducing a new way for casing damage warning. This software uses the support vector machine and fuzzy evaluation method in the algorithm. The support vector machine method can solve the problem of small sample optimal classification. The industry-leading fuzzy evaluation method contains expert experience and can solve nonlinear regression and classification, while logical regression algorithm can only solve linear problems.

6. Conclusions

The above research shows that the number of casing damaged wells in mature old oilfields has been increasing year by year, making it a serious issue. Casing failure can be divided into many types and can occur at various sections. The time when casing failure occurs is closely related to the time when oilfields adjust development strategies. Casing failure can be caused by a variety of factors. Conventional technology serves as the main method for preventing and controlling casing damage but is not effective. No integrated system combining the preventing and controlling method has been introduced. Therefore, the strategy of casing damage prevention and control in China and other countries shall be focused on “prevention” rather than “control”, and more research in the following fields shall be conducted: 1) the mechanism research, especially for the casing failure caused by geomechanical stress changes; 2) the role of stress change in the prediction model of casing failure; 3) the research and development of new casing failure detection equipment based on artificial intelligence, and the investigation of the adaptability of new technologies such as visual logging and array acoustic waves; 4) the development of an integrated system for preventing and controlling of casing failure.

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